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Entanglement and Quantum Superposition of a Macroscopic - Macroscopic system

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Abstract Two quantum Macro-states and their Macroscopic Quantum Superpositions (MQS) localized in two far apart, space – like separated sites can be non-locally correlated by any entangled couple of single-particles having interacted in the past. This novel “Macro - Macro” paradigm is investigated on the basis of a recent study on an entangled Micro-Macro system involving $N \approx 10^5$ particles. Crucial experimental issues as the violation of Bell’s inequalities by the Macro - Macro system are considered.

Keywords Entanglement · Schrödinger Cat

The recent demonstration of the nonlocality of a Micro-Macro quantum system composed by $N \simeq 10^5$ photons organized in a nearly decoherence-free Macroscopic Quantum Superposition (MQS) [1,2,3,4] as well as the work done in the recent past involving photons and atoms [6,7,8] appear to having brought to an end the search for a plausible realization of the famous Schrödinger’s 1935 “paradox” [5]. Indeed these results have finally removed any paradoxical aspect of the “paradox” at the cost of raising more advanced issues e.g. regarding the MQS de-coherence. As it is well known, a wealth of cogent and still unresolved conceptual issues deeply rooted in the foundations of Quantum Mechanics are bound to the old paradigm. First, the question regarding the “localization” and the “classicality” of the wavefunction of macroscopic systems, i.e. the issue of “macrorealism” epitomized by Einstein in a 1954 letter to Born by the sentence “*Narrowness respect to the macro-coordinates is a property not only independent of the principles of quantum mechanics but also incompatible with them*” [9,3]. Second, the intriguing in-

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terplay of the MQS dynamics with the nonlocal correlations established with another microscopic object. This “Micro-Macro” nonlocality paradigm, represented schematically in Figure 1, indeed coincides with the Schrödinger’s Cat (SC) issue, a concept born in the same year 1935 in which Einstein, Podolsky and Rosen (EPR) set forth, somewhat unwillingly the fundamental idea of nonlocality, i.e. of the, according to Schrödinger, “*characteristic trait of quantum mechanics, the one that enforces its entire departure from the classical line of thought*” [10,11].

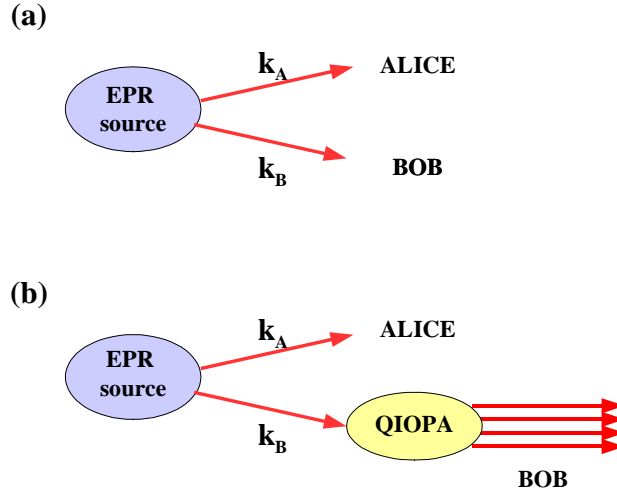


Fig. 1 (a) Generation of an entangled photon pair by spontaneous parametric down conversion (SPDC) in a NL crystal: (b) Single-photon quantum injected optical parametric amplification (QI-OPA) in a Micro - Macro entangled configuration.

The content of present work goes *beyond* the SC conceptual scheme as it ventures into the still explored field of “Macro-Macro” entanglement, i.e. established between two far apart, space-like separated MQS’s. By introducing this new paradigm, and by striving for an experimental realization we intend to complete the intriguing quantum - classical scenario which involves some most fundamental quantum resources, viz: EPR nonlocality, entanglement, interference and de-coherence of Macro-states. Aimed at this purpose and in view to our actual experimental commitment, we believe that the simplest way to construct an overall Macro-Macro apparatus is to combine in a smart way two of the efficient high-gain quantum-injected optical parametric amplifiers (QI-OPA)’s successfully adopted for the recent Micro-Macro demonstration as well as for previous studies on phase-covariant quantum cloning and no-signaling [1,12,13]. The schematic diagram of the standard

QI-OPA device is presented in Figure 2 and its properties may be outlined as follows.

An entangled pair of two photons with wavelength (wl) λ in the singlet state $|\Psi^-\rangle_{A,B} = 2^{-\frac{1}{2}}(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B)$ was produced through a Spontaneous Parametric Down-Conversion (SPDC) by the BBO nonlinear (NL) crystal 1 (C1) pumped by a pulsed UV pump beam at wl $\lambda_P = \lambda/2$. There $|H\rangle$ and $|V\rangle$ stand, respectively, for single photon kets with horizontal ($\vec{\pi}_H$) and vertical ($\vec{\pi}_V$) polarization ($\vec{\pi}$) while the labels A (Alice), B (Bob) refer to particles associated respectively with the spatial modes \mathbf{k}_A and \mathbf{k}_B and represent the two space-like separated Hilbert spaces coupled by entanglement. The excitation source was an amplified mode-locked laser beam frequency-doubled by second-harmonic generation and providing the OPA excitation field at the UV wavelength $\lambda_P = 397.5nm$. The photon belonging to mode \mathbf{k}_B of each EPR pair generated by SPDC was injected into an optical parametric amplifier consisting of a BBO NL crystal 2 (C2) pumped by the strong UV pump beam. A time delay secured the time superposition in the OPA of the excitation UV pulse and of the injection photon wavepackets. The injected single photon and the UV pump beam \mathbf{k}'_P were superimposed by means of a dichroic mirror (DM). The crystal 2, cut for collinear operation along \mathbf{k}_B , emitted over modes of linear $\vec{\pi}$, i.e. $\vec{\pi}_H$ and $\vec{\pi}_V$. The parametric interaction Hamiltonian $\hat{H}_B = i\chi\hbar\hat{a}_H^\dagger\hat{a}_V^\dagger + h.c.$ acts on the single spatial mode \mathbf{k}_B where \hat{a}_π^\dagger is the creation operator associated with $\vec{\pi}$. The main feature of \hat{H}_B is its "phase-covariance", i.e. invariance under $U(1)$ ϕ -transformations, for qubits $|\phi\rangle$ representing "equatorial" $\vec{\pi}$ -states, i.e. $\vec{\pi}_\phi = 2^{-1/2}(\vec{\pi}_H + e^{i\phi}\vec{\pi}_V)$, $\vec{\pi}_{\phi\perp} = \vec{\pi}_\phi^\perp$, in a Poincaré sphere representation with poles: $\vec{\pi}_H$ and $\vec{\pi}_V$. According to the quantum cloning theory these qubits $|\phi\rangle$, expressed in terms of a single phase $\phi \in (0, 2\pi)$ in the basis $\{|H\rangle, |V\rangle\}$, span a privileged Hilbert subspace corresponding to an "optimum fidelity", i.e. to a minimum amplifier noise and a minimum decoherence of the amplified field [3]. We can then re-write: $\hat{H}_B = \frac{1}{2}i\chi\hbar e^{-i\phi}(\hat{a}_\phi^{\dagger 2} - e^{i2\phi}\hat{a}_{\phi\perp}^{\dagger 2}) + h.c.$ where $\hat{a}_\phi^\dagger = 2^{-1/2}(\hat{a}_H^\dagger + e^{i\phi}\hat{a}_V^\dagger)$ and $\hat{a}_{\phi\perp}^\dagger = 2^{-1/2}(-e^{-i\phi}\hat{a}_H^\dagger + \hat{a}_V^\dagger)$. We shall consider the fields \hat{a}_+^\dagger , \hat{a}_-^\dagger corresponding to $\phi = 0$. The generic $\vec{\pi}$ -state of the injected qubit $|\psi\rangle_B$ evolves into the output state $|\Phi^\psi\rangle_B = \widehat{U}_B|\psi\rangle_B$ according to the OPA unitary: $\widehat{U}_B = -i\hat{H}_B t/\hbar$. The QI-OPA apparatus generates in any equatorial $\vec{\pi}$ -basis $\{\vec{\pi}_\phi, \vec{\pi}_{\phi\perp}\}$, the Micro-Macro entangled state commonly referred to as the "SC State" [14].

$$|\Sigma\rangle_{A,B} = 2^{-1/2}(|\Phi^\phi\rangle_B \otimes |1\phi^\perp\rangle_A - |\Phi^{\phi\perp}\rangle_B \otimes |1\phi\rangle_A) \quad (1)$$

where the "Macro-states" are:

$$\begin{aligned} |\Phi^\phi\rangle_B &= \sum_{i,j=0}^{\infty} \gamma_{ij} |(2i+1)\phi; (2j)\phi^\perp\rangle_B \\ |\Phi^{\phi\perp}\rangle_B &= \sum_{i,j=0}^{\infty} \gamma_{ij} |(2j)\phi; (2i+1)\phi^\perp\rangle_B \end{aligned}$$

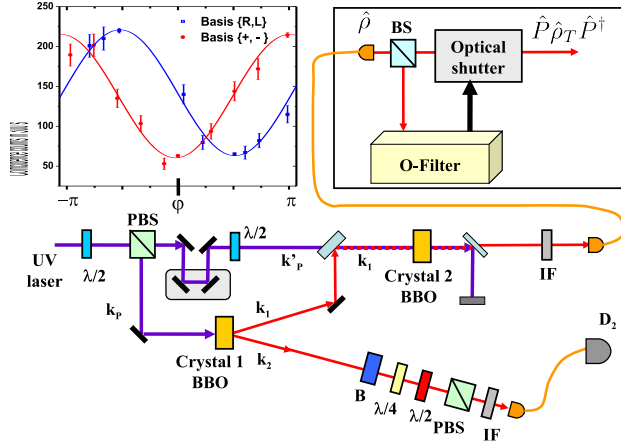


Fig. 2 QI-OPA setup for the Micro - Macro test.

with: $\gamma_{ij} \equiv C^{-2}(-\frac{\Gamma}{2})^i \frac{\Gamma^j}{2} \frac{\sqrt{(1+2i)!(2j)!}}{i!j!}$, $C \equiv \cosh g$, $S \equiv \sinh g$, $\Gamma \equiv S/C$, being g the NL gain. There $|p\phi; q\phi^\perp\rangle_B$ stands for a Fock state with p photons with $\vec{\pi}_\phi$ and q photons with $\vec{\pi}_{\phi^\perp}$ over the mode \mathbf{k}_B . The macrostates of Eq.(2-3) $|\Phi^\phi\rangle_B$, $|\Phi^{\phi^\perp}\rangle_B$ are orthonormal and exhibit observables bearing macroscopically distinct average values. In typical experiments, under *single particle* injection, a gain $g \simeq 4.5$ was attained leading to a number of output photons $\mathcal{N} \simeq 5 \times 10^4$. A NL gain $g = 6$ and a photon number $\mathcal{N} \simeq 10^6$ was also attained with no substantial changes of the apparatus. Indeed, an unlimited number of photons could be generated by the QI-OPA technique, the only limitation being the fracture of the NL crystal in the focal region of the laser pump. All the QI-OPA amplification properties can be greatly enhanced by injection of *multi-particle* qubits, e.g. by spin-1, 2-photon qubits [2]. In summary, the QI-OPA operation acts as a perfect *information preserving quantum map* that transforms nonlocally, i.e. acting between two space-like separated sites, any injected single particle Micro-qubit, or a quantum superposition, into a corresponding *Macro-qubit* or a Macroscopic Quantum Superposition: $(\alpha|\phi\rangle_B + \beta|\phi^\perp\rangle_B) \Rightarrow (\alpha|\Phi^\phi\rangle_B + \beta|\Phi^{\phi^\perp}\rangle_B)$. The two interference fringe patterns shown in left Inset of Figure 2 represent the results of a recent demonstration of Micro-Macro entanglement adopting two different measurement bases.

In order to inspect at a deeper level the interference properties of our MQSt, let's determine the Wigner function of the output field under injection of the single-particle $|\psi\rangle_B$, by first evaluating the *symmetrically ordered characteristic function* of the set of complex variables $(\eta, \eta^*, \xi, \xi^*) \equiv \{\eta, \xi\}$: $\chi_S\{\eta, \xi\} \equiv \langle\psi| D[\eta(t)]D[\xi(t)]|\psi\rangle$ expressed in terms of the *displacement operators* $D[\eta(t)] \equiv \exp[\eta(t)\hat{a}_+(0)^\dagger - \eta^*(t)\hat{a}_+(0)]$ and $D[\xi(t)] \equiv \exp[\xi(t)\hat{a}_-(0)^\dagger - \xi^*(t)\hat{a}_-(0)]$ where: $\eta(t) \equiv (\eta C - \eta^* S)$; $\xi(t) \equiv (\xi C - \xi^* S)$. The Wigner function of the *phase-space variables* $(\alpha, \alpha^*, \beta, \beta^*) \equiv \{\alpha, \beta\}$ is the 4th-dimensional Fourier transform of $\chi_S\{\eta, \xi\}$ [14]. A closed form evaluation of $\chi_S\{\eta, \xi\}$

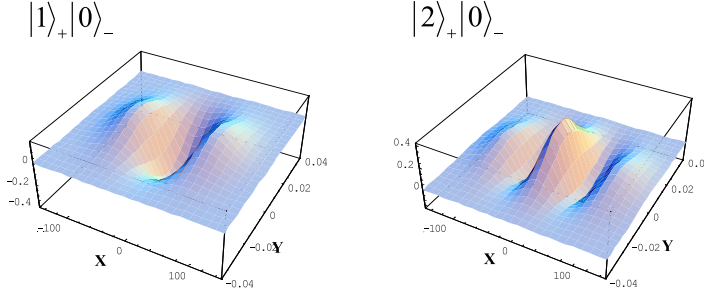


Fig. 3 Wigner functions of the QI-OPA amplified states with gain $g = 4$. The scales on different graphs are different owing to the large squeezing process affecting the amplified fields. The Dirac symbols at the top of the figure represent the injection states of the OPA corresponding to the Wigner plots below.

leads to the *exact* expression:

$$\begin{aligned}
 W(\alpha, \beta) &= \frac{1}{\pi^4} \int \exp(\eta^* \alpha - \eta \alpha^*) \exp(\xi^* \beta - \xi \beta^*) \\
 &\exp[-(|\eta(t)|^2 + |\xi(t)|^2)] \left(\frac{1}{4} - \frac{|\eta(t)|^2}{8} \right) d^2 \eta d^2 \xi = \\
 &= -\overline{W}(\alpha) \times \overline{W}(\beta) \times \mathcal{F}(X)
 \end{aligned}$$

where the “interference term” $\mathcal{F}(X)$ accounts for the quantum interference, i.e. the superposition character of the MQS, of the two otherwise decoupled quasiprobability functions: $\overline{W}(\alpha) \equiv \frac{2}{\pi} \exp(-|\Delta_A|^2)$ and $\overline{W}(\beta) \equiv \frac{2}{\pi} \exp(-|\Delta_B|^2)$ where: $\Delta_A = \frac{1}{\sqrt{2}}(\gamma_{A+} - i\gamma_{A-})$, $\Delta_B = \frac{1}{\sqrt{2}}(\gamma_{B+} - i\gamma_{B-})$ and the *squeezing variables* are: $\gamma_{A\pm} = (\alpha \pm \beta^*)e^{-g}$, $\gamma_{B\pm} = (\alpha^* \pm \beta)e^{-g}$. The term \mathcal{F} is a polynomial function of $X \equiv |\Delta_A + \Delta_B|$: for 1- particle injection is: $\mathcal{F}(X) = (1 - X^2)$, for 2-particle: $\mathcal{F}(X) = (1 - 2X^2 + \frac{1}{4}X^4)$. A 3-dimensional representation of $W(\alpha, \beta)$ for 1 and 2 photon injection on the input mode with mode $\vec{\pi}_+ = 2^{-1/2}(\vec{\pi}_H + \vec{\pi}_V)$ and zero photon injection on $\vec{\pi}_- = 2^{-1/2}(\vec{\pi}_H - \vec{\pi}_V)$. Note, most important, the absence of *definite positivity* of $W\{\alpha, \beta\}$ over the overall phase space $\{\alpha, \beta\}$ which assures the quantum character of the QI-OPA generated system [14,15,16].

In several applications the QI-OPA generated Macrostate $\rho \equiv |\Phi\rangle_B \langle\Phi|$ may be conveniently transformed, before the final measurement, by the O-Filter device shown in Figure 2, Right Inset. This device works very generally as follows. A beam-splitter (BS) with low reflectivity $R = (1 - T) \ll 1$ directs towards a subsidiary measurement apparatus a small portion of the set of particles associated with the main beam, i.e. with the reflected state: $\rho_R \equiv tr_T \rho$, the trace being taken over the variables of the “transmitted” field. Depending on the measurement outcomes related to some prescribed properties of $|\Phi\rangle_B$, the apparatus drives, through a suitable prescribed *program* P , a fast electro-optical device that may generally transforms the macrostate $\rho_T = tr_R \rho \approx \rho$ emerging from the BS into the field: $(P\rho_T P^+)$. For instance, as shown in Figure 2 it can simply shut off, or open the path to the main

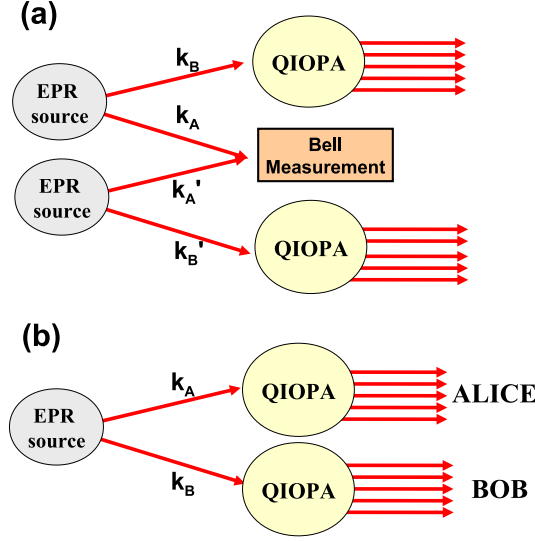


Fig. 4 Macro - Macro entanglement via (a) entanglement swapping (b) double QI-OPA synchronization.

beam by a Pockels-cell fast optical-shutter, a device recently realized and tested in our laboratory [17]. This subsidiary device, denoted by the symbol OF henceforth, enables in general several interesting quantum operations, e.g. aimed at the assessment of the *hidden-nonlocality* of ρ , according to a 1995 proposal by Popescu, widely discussed in the literature but, we believe, never realized experimentally [18, 19, 20].

The diagrams reported in Figure 4 suggest the simplest, and most convenient arrangements of QI-OPA devices useful for our purposes. Let us discuss them separately.

a) QI-OPA entanglement-swapping. Two independent and equal QI-OPA's, Figure 2 (a), each possibly followed by a OF device can be correlated, after a careful space-time synchronization of all injected and UV pump pulses, by a standard entanglement-swapping protocol adopting, as usual an intermediate 50/50 beam-splitter BS_A with input and output modes $(k_A, k_{A'})$ and $(\tilde{k}_A, \tilde{k}_{A'})$, respectively [21, 22]. Precisely, the overall Macrostate at the output of the two QI-OPA devices connected via the Microstates associated with the *input* modes of BS_A can be expressed as follows: $|\Phi\rangle_{AB} = |\Sigma\rangle_{A,B} \otimes |\Sigma\rangle_{A',B'}$ where the structure of two entangled Macro-states are given by Eq.1 and by the symbol swap: $(A, B) \Rightarrow (A', B')$. These states are generated by two equal QI-OPA's which are made to interact via BS_A through the orthogonal sets of single-particle states $\{|1\phi^\perp\rangle_A, |1\phi^\perp\rangle_{A'}\}$ and $\{|1\phi\rangle_A, |1\phi\rangle_{A'}\}$. The overall pure state: $|\Phi\rangle_{AB} = [\Phi_A^+ \otimes \Phi_B^+ - \Phi_A^- \otimes \Phi_B^- - \Psi_A^+ \otimes \Psi_B^+ + \Psi_A^- \otimes \Psi_B^-]$ may be then expressed as a sum of products of Bell states defined in the two Hilbert spaces spanned by all eigenvectors. Precisely, the entangled Micro-states defined at the input of BS_A are: $\Phi_A^\pm = 2^{-\frac{1}{2}} (|1\phi\rangle_A \otimes |1\phi\rangle_{A'} \pm |1\phi^\perp\rangle_A \otimes |1\phi^\perp\rangle_{A'})$ and $\Psi_A^\pm = 2^{-\frac{1}{2}} (|1\phi\rangle_A \otimes |1\phi^\perp\rangle_{A'} \pm |1\phi^\perp\rangle_A \otimes |1\phi\rangle_{A'})$ while the Macro-states

realized at the modes $\mathbf{k}_B, \mathbf{k}_{B'}$ are: $\Phi_B^\pm = 2^{-\frac{1}{2}} (|\Phi^\phi\rangle_B \otimes |\Phi^\phi\rangle_{B'} \pm |\Phi^{\phi\perp}\rangle_B \otimes |\Phi^{\phi\perp}\rangle_{B'})$, $\Psi_B^\pm = 2^{-\frac{1}{2}} (|\Phi^\phi\rangle_B \otimes |\Phi^{\phi\perp}\rangle_{B'} \pm |\Phi^{\phi\perp}\rangle_B \otimes |\Phi^\phi\rangle_{B'})$. The expression of $|\Phi\rangle_{AB}$ just given shows that the original entanglement condition existing within the two separated QI-OPA systems (k_A, k_B) and $(k_{A'}, k_{B'})$ is swapped to the “extreme” modes k_B and $k_{B'}$ by any joint Bell single-particle measurement made on the *output* modes of $BS_A : (\tilde{k}_A, \tilde{k}_{A'})$. In other words, the overall state $|\Phi\rangle_{AB}$ is a superposition that is “reduced” by any measurement taking place at the output of BS_A : e.g., a single-particle measurement of the Micro-Micro Φ_A^+ leads to a sudden reduction of $|\Phi\rangle_{AB}$ to the corresponding Macro-Macro entangled state Φ_E^+ . This is the relevant result we sought. The swapping procedure can be repeated many times by steps involving a chain of BS's connected by EPR entangled pairs, and lead to the concept of the *quantum repeater*, a device conceived for efficient long range communication and cryptography [23,24]. As far as this issue is concerned, we only remind here the enormous *degree of redundancy*, $\mathcal{N} \simeq 10^5$, implied by the QI-OPA scheme by which the information is carried by Macro-qubits composed by thousand or millions of particles acting simultaneously, in parallel.

(b) QI-OPA double amplification. This solution, shown in Figure 4 (b), consists of the synchronous QI-OPA amplification on both arms of the simple Micro-Micro EPR scheme shown in Figure 1-(a). Two independent and equal QI-OPA amplifiers, possibly followed by two corresponding OF devices will act independently on the EPR entangled modes k_A and k_B of a single entangled pair by the parametric evolution operators $\widehat{U}_A, \widehat{U}_B$ corresponding to the hamiltonians $\widehat{H}_A, \widehat{H}_B$ which are formally identical but for the swap of symbols: $A \Rightarrow B$. The output Macro-state is then simply obtained by the Micro-Macro state $|\Sigma\rangle_{A,B}$, Eq.1 transformed into: $(\widehat{U}_A \otimes I) |\Sigma\rangle_{A,B} = 2^{-1/2} (|\Phi^\phi\rangle_A \otimes |\Phi^{\phi\perp}\rangle_B - |\Phi^{\phi\perp}\rangle_A \otimes |\Phi^\phi\rangle_B)$, i.e. the Macro - Macro singlet we were looking for.

The assessment of the bipartite entanglement of ρ existing between the far apart sites A and B may be carried out by joint correlation measurements between two standard measurement apparata located in A and B , as done successfully in [1] for the Micro-Macro case. Owing to the unavoidable *squeezed-vacuum noise* implied by any active parametric amplification process, i.e. the necessary counterpart of the *no-cloning* theorem, each measurement will be preceded by a subsidiary state-projection transformation carried out by two OF devices acting on the QI-OPA outputs states in correspondence of arms A, B . The program P of the OF filter may consist of the “Orthogonality Filter P ” described in [2]. A somewhat more sophisticated procedure is requested for a correct interpretation of the outcomes of any test of Bell-inequality violation carried out at the measurement sites A and B . According to Popescu “*to prove that a quantum state is local, one must show that the correlations between the results of any local experiment can be described by a local hidden variable*” (*LHV*) model[18]. Then, to prevent any LHV interpretation, as suggested by [20], the pre-measurement provided by two OF devices should imply the adoption of corresponding OF programs P independent of the *settings* of the main measurement apparata operat-

ing at A and B . In other words, they should be once again *phase-covariant* and, according to a recent proposal, would determine a suitable “threshold condition” to the measured state ρ_T [25]. The structure of our experimental apparatus includes a wide range of experimental options apt to comply with all these requirements. Of course, our recent experience in the field tells us that the successful realization of the proposed experiments requires a perfect control of all parts of the complex apparatus, a task difficult to achieve in practice.

In conclusion, we have reported a feasible proposal that may lead to a relevant conceptual breakthrough in the context of some most intriguing foundational aspects of modern Physics. Because of the conceptual simplicity, this approach may contribute to enlighten some parts of the elusive boundaries still existing between the “quantum” and the “classical” territories.

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